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Approaches to Obtain Tunable Diode Lasers for Air Monitoring Between 2 and 2.5 μm on InP

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ABSTRACT

Alternative approaches for developing 2.0-2.5 μm single frequency semiconductor lasers are reviewed. Room temperature lasers in this wavelength range are important for the development of absorption spectroscopy instruments used in environmental monitoring and life support for space applications. In spite of significant efforts towards the growth and fabrication of lasers using the GaSb-based material system, room temperature, single frequency lasers in the 2-2.5 μm wavelength range are not yet available. As an alternative to the GaSb-based material system, novel techniques using the mature InP-based material system (which is potentially more suitable for single frequency laser fabrication) are being investigated. These include: highly strained InGaAs quantum well layers, graded buffer layers, laterally confined growth, and InGaAsN quantum well layers. In this paper, we will review the current status and limitations of these techniques to develop ambient temperature, single frequency lasers.

INTRODUCTION

With the prospect of long-duration space shuttle flights and future space stations, there is a need for monitoring toxic and volatile gases in these enclosed environments. One method to monitor these gases is absorption spectroscopy, which can be accomplished with relatively small size and power consumption using ambient temperature, single frequency, tunable diode lasers (TDLs). The wavelength of a TDL can be temperature or current tuned to coincide with a specific absorption band of a molecule. Detection techniques based on the modulation of laser current yield sensitivities for measuring concentrations of one part per million (ppm) or less. The instrument's sensitivity, speed, and ability to quickly discriminate gases makes them ideal for life support applications within the space shuttle or space station [1].

Room temperature lasers in the 2.0-2.5 μm wavelength range will be an important part of the development of absorption spectroscopy instruments used in environmental monitoring and life support for space applications. Presently, TDLs in the 2 - 2.5 μm wavelength range are being developed using the antinomide-based alloys. Although room-temperature lasers have been demonstrated [2,3], the development of single frequency lasers has been slow due to many growth and fabrication issues related to this material system. Conversely, the maturity of the InP-based material system developed by the telecommunications industry has lead to the investigation of new approaches which could lead to extending the lasing wavelength of InP-based lasers beyond its present limits.

HIGHLY STRAINED INGAAS QUANTUM WELL LASERS

Figure 1 shows the relationship between the lattice constant (atomic spacing) and emission wavelength of certain III-V semiconductor alloys including InAsP and InGaAs. The solid line indicates a lattice constant of 5.8686Å, which is the lattice constant of an InP substrate. A diode laser consisting of an epitaxially grown, lattice matched InGaAs layer would have an emission wavelength of 1.65 μm. As the indium concentration of the InGaAs layer is increased, the wavelength also increases. However, the larger lattice constant results in the layer being subjected to a compressive strain with relation to the InP substrate. For every strained composition, there is a thickness above which the material will no longer accommodate this strain. Once a material has reached this "critical thickness", the material quality rapidly degrades, and a high number of dislocation defects are generated.

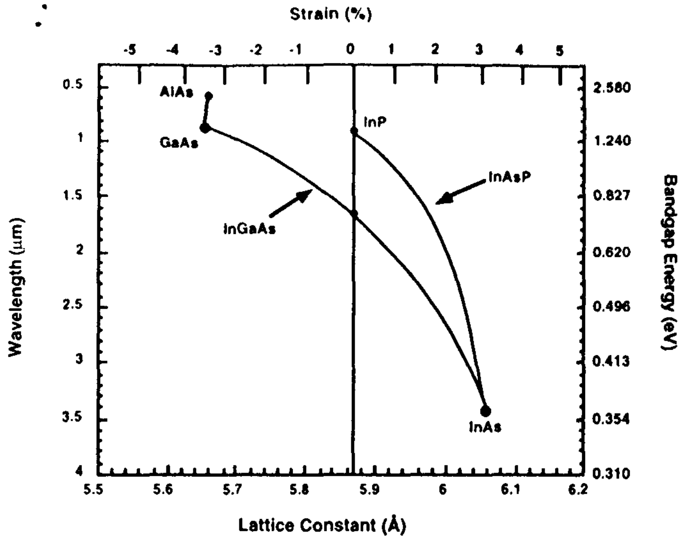

Figure 1: Material parameters of certain III - V alloy semiconductors including InAsP and InGaAs.

To accommodate the highly strained InGaAs alloy needed for wavelengths beyond 1.7 µm, quantum wells with thicknesses less than 150 Å are used. The wavelength of the fundamental transition of a strained InGaAs quantum well can be calculated using a finite square well potential. The calculated wavelength as a function of quantum well thickness with InP barriers is shown in Figure 2. The wavelength of the quantum well is shorter than for bulk material due to the quantum confinement effect. The dashed line identifies the maximum wavelength achievable with various indium compositions, x, without exceeding the critical thickness calculated on the basis of the force balance model proposed by Matthews and Blakeslee [4]. This calculation shows that the strained InGaAs quantum well on InP substrate may be used for lasers with emission wavelengths out to 2.1 µm.

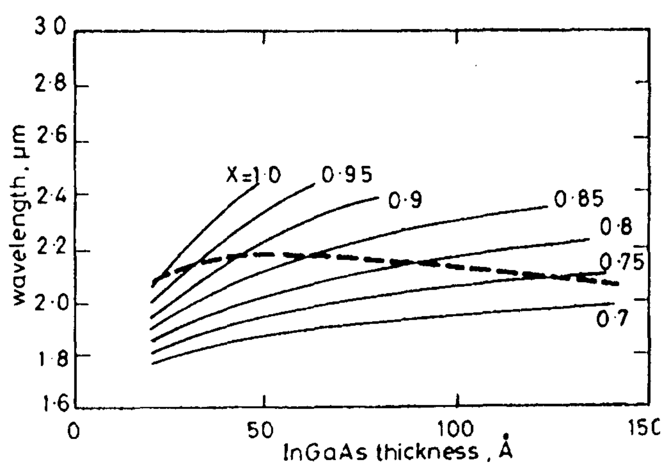

Figure 2: Calculation of wavelength vs. thickness for compressively strained $In_xGa_{1-x}As/InP$ compositions for x=0.7 to 1.0 . The dashed line represents the critical thickness limit for the strained layer.

We have previously reported the room temperature operation of InGaAs/InP quantum well lasers at wavelengths as long as 2.06 µm [5]. The light versus current characteristics of a single-mode distributed feedback laser at several temperatures are shown in Figure 3. Threshold currents as low as 22 mA and output powers per fact of 1.5 mW at room temperature for a 350 µm long device have been achieved.

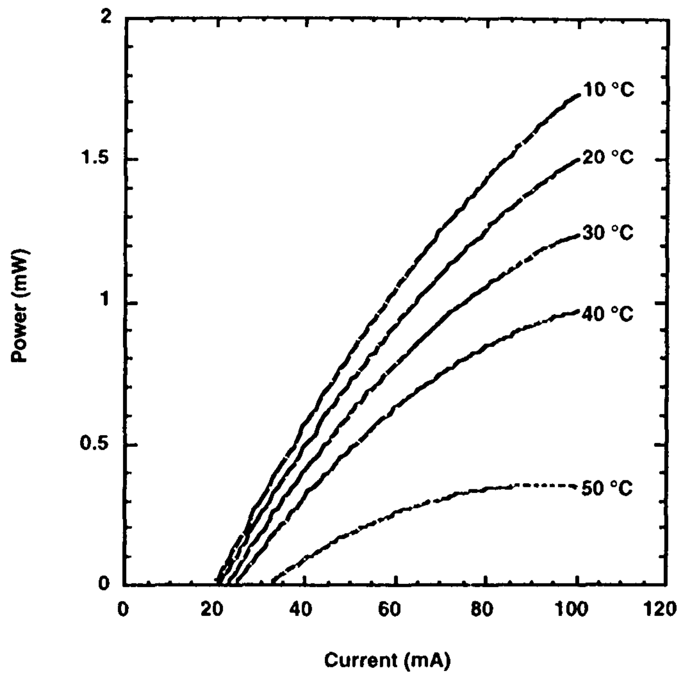

Figure 3: Continuous light output against current for a tunable diode laser at ~2.05 µm at several temperatures.

The optical spectrum of the single frequency InGaAs/InP distributed feedback laser at 2.055 µm is shown in Figure 5. The long-term reliability of these highly strained devices has been verified, and TDLs at a wavelength of 2.0465 µm have been fabricated and delivered for the detection of CO_2 isotopes as part of the Mars '98 mission.

Attempts to increase the emission wavelength of highly strained InGaAs quantum well lasers beyond 2.08 µm resulted in poor quality crystal growth with little or no luminescence emission from the wafers. It has been concluded experimentally that 2.07-2.08 µm is the longest wavelength that reliable InP-based quantum well lasers could be fabricated using the present growth and fabrication techniques.

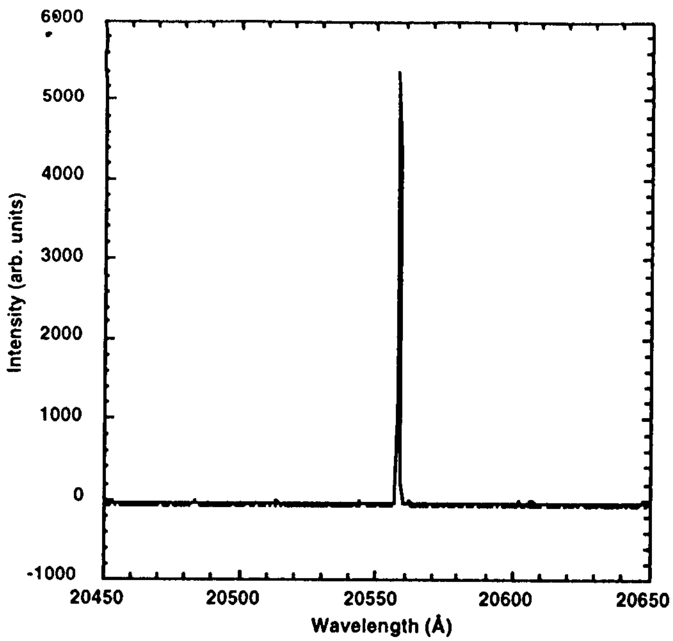

Figure 4: Single frequency optical spectra of a tunable diode laser operating at 2.055 μm.

GRADED SUBSTRATES

To increase the wavelength of InGaAs quantum well lasers beyond 2.08 μm, the most practical approach is the use of ternary substrates of InAsP or InGaAs with a lattice constant larger than InP. InAsP would be the substrate of choice due to its larger bandgap and lower refractive index providing both electrical and optical confinement for the laser. InAsP substrates with low arsenic concentrations (<10 %) have been fabricated. However, due to difficulties in controlling the fabrication process, the substrates have been very non-stochiometric with stress fractures throughout the substrates, and this effect worsens with increased arsenic. Despite these difficulties, strained quantum well lasers using an $InAs_{0.08}P_{0.92}$ substrate with a lattice constant of 5.8860Å have been fabricated, although the longest wavelength measured was only 1.75 μm [6].

With the lack of high quality ternary substrates, one must then develop a way to accommodate the difference in lattice constant between the InP substrate and an epitaxially grown InAsP layer. When a mismatched layer is grown, it first distorts elasticity to match the substrate material across the interface (strain). As the layer thickness increases the stress in the film may exceed the elastic limit (critical thickness) and dislocations are introduced. These dislocations propagate up through the device and seriously degrade its performance.

Dislocations can be reduced by growing a thick, compositionally graded layer from InP to InAsP. By growing this buffer layer, the upward propagating dislocations are slowly turned over to propagate parallel to the epitaxial layer. Various forms of these graded substrates have been developed. They can be linearly or step-graded[7]. Figure 5a and 5b are Nomarski phase contrast micrographs showing the improved material quality when a step-graded buffer layer is used.

a.) b.)

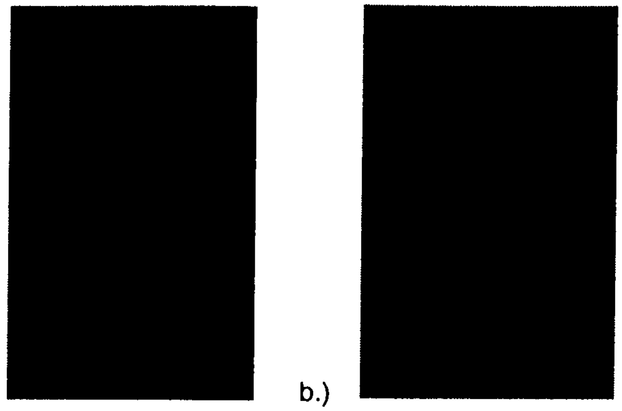

Figure 5: Nomarski phase contrast micrographs of InAsP grown directly on InP (a.), and using a step graded buffer layer (b.).

Although the graded substrate technique is widely used for photodetectors in the 2.5 μm range, very few results have been presented using this technique for lasers. To date, the best laser results have been demonstrated using a 20 μm thick buffer which incorporated both a linearly graded and step graded compositional change [8]. Using this technique, the device was able to accommodate the 2.31% mismatch between the InP substrate and the bulk InGaAs active layer. The wavelength of the device was 2.45 μm, but operated only up to temperatures of 210K. The limited temperature performance of the device can be attributed to poor electrical and optical confinement due to the InAsP wavelength (and therefore the band-gap energy) changing more rapidly than InGaAs for increasing indium composition(see Figure 1). In an attempt to increase the operating temperature, we are presently working on combining the graded substrate technology with our knowledge of highly strained quantum well lasers. By combining these two technologies, we believe lasers with wavelengths of approximately 2.3 μm can be fabricated with enough electrical and optical confinement to operate at room temperature.

LATERALLY CONFINED GROWTH

Another approach to achieving longer wavelength emission would be to increase the allowed critical thickness of the strained quantum wells. This would be a simpler approach than the graded substrates since it would alleviate the thick, often complex, buffer layer. In addition, the thick cladding layers of the laser could once again be InP, which not only improves the electrical and optical confinement, but also simplifies the epitaxial growth.

A novel method to increase the critical thickness has been demonstrated for the SiGe/Si [9] and InGaAs/GaAs [10] material systems. By growing strained material that is confined to small areas, either with etched trenches or prepatterned mesas of approximately 2 μm width, the critical thickness at which dislocations begin to appear has been increased by at least a factor of four. By exploiting this strain relief mechanism which occurs at the mesa edges, a dislocation-free strained InGaAs/GaAs multi quantum well structure was grown with a well thickness which exceeded the critical thickness of the same structure grown on unpatterned substrates[11].

As discussed previously, the present emission wavelength for lasers grown directly on InP substrates is limited to 2.08 μm due to the critical thickness of the highly strained quantum well. If the critical thickness of the quantum wells were to be increased using this approach, then it is conceivable to obtain lasers on InP substrates which would approach an emission wavelength of 2.5 μm.

INGAASN ALLOY

Similar to the InP-based material system, the lasing wavelength of GaAs-based lasers are limited by the critical thickness of the InGaAs quantum well. When fabricated to operate at 0.98 μm for fiber-amplifier pump sources or 1.06 μm for Nd-YAG pump sources, the critical thickness of these InGaAs/GaAs lasers is not exceeded. However, there has been a strong push to develop GaAs-based 1.3 μm telecommunication lasers due to the high temperature performance inherent to this material system. Unfortunately, using standard growth technologies, this wavelength has yet to be obtained, with an apparent upper limit (due to the critical thickness) of approximately 1.1 μm.

Recently, a new material system, InGaAsN, is being developed, to extend the operating wavelength of lasers grown on GaAs substrates. Figure 6 shows the material parameters for several III-V semiconductors including GaAsN. The inclusion of nitrogen atoms into the GaAs lattice not only has the effect of making the lattice smaller which is to be expected, but it also has the unique behavior of making the bandgap energy smaller and hence the operating wavelength longer. This allows one to extend the usable wavelength beyond that which is presently obtained using InGaAs.

Adding indium to GaAs, i.e. making an InGaAs alloy, increases the lattice constant. However, making a GaAsN alloy by adding nitrogen to GaAs decreases the lattice constant. Therefore, InGaAsN can be grown lattice matched to either GaAs or InP by adjusting the indium and nitrogen contents, and as shown by the dashed line in Figure 6, adding either nitrogen or indium has the effect of lengthening the emission wavelength.

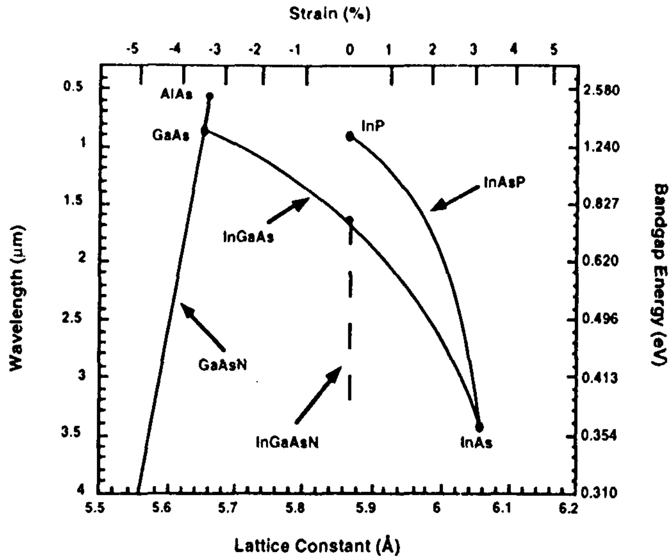

Figure 6: Material parameters of GaAsN and InGaAsN.

InGaAsN/GaAs lasers with wavelengths approaching 1.3 μm have been demonstrated [12], and the desired improvement in high temperature performance was observed. However, nitrogen incorporation has proven to be more difficult as the indium concentration is increased. Although it is estimated that nitrogen percentages of only 1.5 % will be needed for InGaAsN quantum wells to reach wavelengths of 2.5 μm on InP, the bonding strength of nitrogen as well as chemical pre-reactions during crystal growth are some problems which must first be resolved before these lasers can be realized.

CONCLUSION

Several approaches to obtain room temperature, continuous wave lasers at 2 - 2.5 μm on InP substrates have been reviewed. We have previously fabricated lasers using highly strained quantum wells in the active region. However, due to critical thickness constraints, the maximum wavelength obtainable for InGaAs quantum wells is approximately 2.08 μm. Therefore, it has become necessary to investigate new techniques which could possibly extend the operating wavelength beyond this present limit. We have initiated a program to pursue the following: graded substrates, laterally confined growth, and the InGaAsN material system. By pursuing these novel techniques, we believe that room temperature, single frequency lasers in the 2 - 2.5 μm range can be achieved using the InP-based material system.

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